

Coherent Structures—Comments on Mechanisms

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1. Introductory remarks

There is now overwhelming evidence that in most turbulent flows, despite the flow field being random, there exist regions moving with the flow where the velocity and vorticity have a characteristic "structure." These regions are called "coherent structures" because within them the large-scale distributions of velocity and/or vorticity remain coherent even as these structures move through the flow and interact with other structures. In most flows the sizes of these structures vary but the distributions of velocity/vorticity remain similar. There is also evidence that there is a significant degree of similarity between these distributions in different flows (Hussain 1986).

Since flow enters and leaves the bounding surfaces of these structures, a useful definition, following Hussain (1986), for coherent structures is that they are "open volumes with distinctive large-scale vorticity distributions."

The following schematic remarks are a personal statement about possible fruitful directions for the study of the dynamics of coherent structures (hereafter CS). Most CS research to-date has been concentrated on the measurement and kinematical analysis of CS; there is now a welcome move to examine the dynamics of CS, by a variety of different methods. A few of them will be described here.

2. The origins of coherent structures

Coherent structures arise by two main types of mechanism.

(i) *Instability (primary or secondary)*

When non-uniform flows are generated at high Reynolds number they are usually unstable, so that some small disturbances to the velocity field amplify. The most unstable disturbances may be small in amplitude but their length scale is usually of the same order as that of the original mean flow. Even as the amplitude of the disturbances grow to the same order as that of the velocity of the original flow, the length scale and flow structure remain similar to that of the original small disturbance, as in the free shear layer (Fig. 1).

Consequently linear stability theory remains of considerable value in analyzing CS and in estimating their consequences, e.g., their effects on noise generation (e.g., Gaster et al. 1985).

Once the primary instabilities have grown secondary instabilities develop, often with vorticity in directions perpendicular to that of the primary instability, for example the "braids" that form in free shear layers with vorticity parallel to the mean flow and that link the primary "roller" vorticities (e.g., Bernal & Roshko 1986).

A general feature of the growth of the primary and secondary instabilities is that they lead to a concentration of vorticity in localized regions in the flow as shown by recent non-linear studies (e.g., Smith 1987). Well-known examples are the rollers and braids in free shear layers, and the spanwise vortices and "horseshoe" vortices in boundary-layer flows. These regions of concentrated vorticity, which occur at Reynolds numbers (based on global or local scales) just great enough for turbulence to persist, are usually found to have characteristics similar to those in coherent structures at high Reynolds numbers.

(ii) *Selective amplification of disturbances by the mean field*

Consider an initially isotropic homogeneous turbulent velocity field introduced into a shear flow. (This is certainly possible on the computer, e.g., Rogallo 1981, and approximately possible in a wind tunnel, e.g., Champagne et al. 1970; it may broadly approximate the turbulence generated at the wall or at the outer interface in the boundary layer, e.g., Townsend 1970.)

Computations, both non-linear by Rogallo (1981), and linear by Lee et al. (1987), show that the shear stretches and rotates the vorticity in such a way that the eddies become elongated and develop

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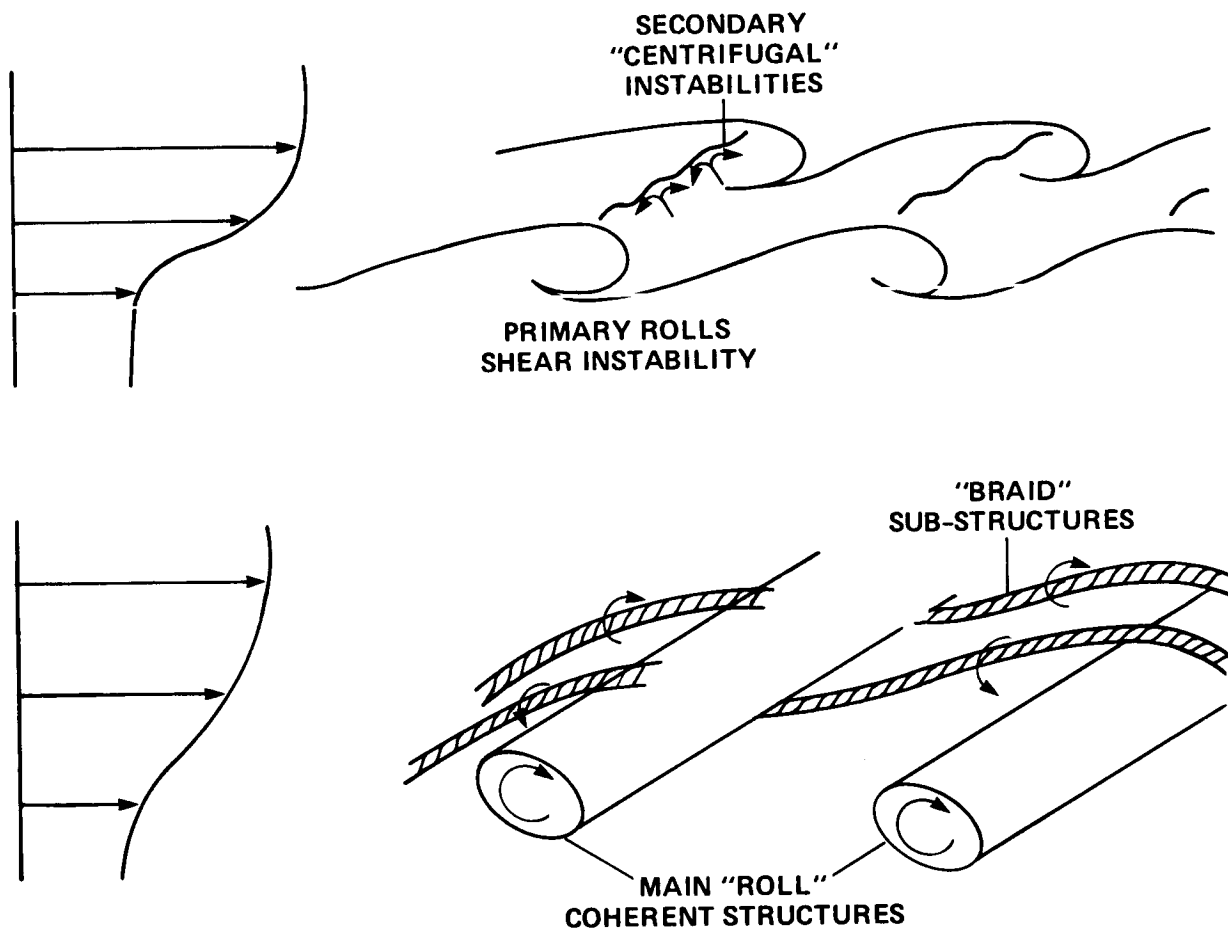


FIGURE 1. Coherent structures generated from instabilities: Primary and secondary instabilities in a free shear layer leading to two kinds of coherent structure — “rolls” and “braids.” The latter are also known as “sub-structures.”

sharper boundaries (Fig. 2). This is the explanation of the evolution of the velocity spectrum in Rogallo's computations from an exponential decay (indicating very smooth velocity distributions in the eddies) to a k^{-2} decay (indicating discontinuities on the large scale). Linear calculations using Rapid Distortion Theory (RDT) also show these effects; similar coherent structures are found as in the non-linear simulations. (The analysis of the RDT spectra needs to be done.)

3. Interactions between a coherent structure and its surrounding flow

After the formation of a CS, its subsequent existence depends on how it interacts with the surrounding flow. This varies considerably between flows.

(i) Uniform flows

Although CS are not generated in uniform flows, they are often moved by the flow or propagate themselves into regions of approximately uniform velocity; CS in wakes far from the body approximate to this case. The simplest type of CS to consider in this situation is the vortex ring or the vortex pair (Maxworthy 1977). These CS preserve their structure, but they always lose some vorticity as they propagate through the flow (Fig. 3a).

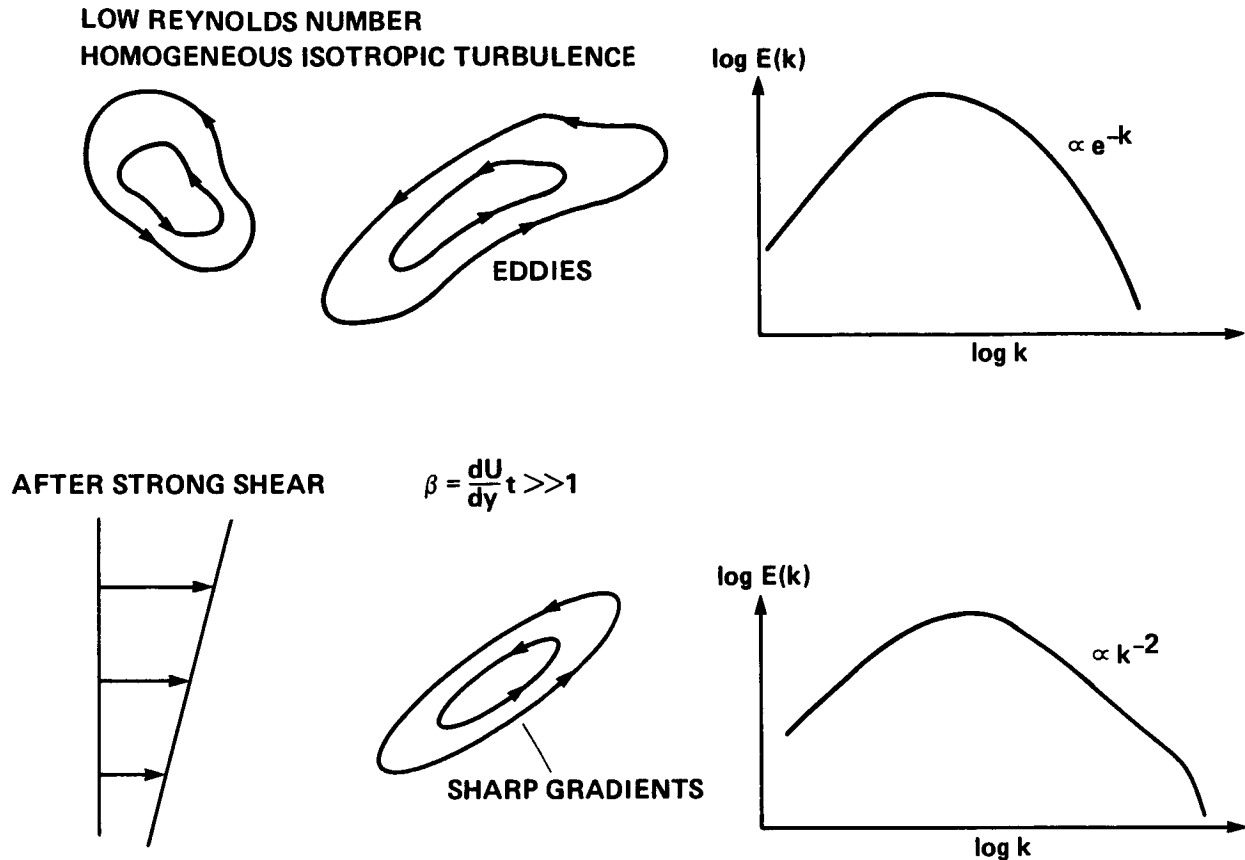


FIGURE 2. Coherent structures generated by deforming a random velocity field. Distortion of a typical eddy or CS as shear is applied to homogeneous turbulence. Note the change in spectra (Rogallo, 1981; Lee et al., 1987)

(ii) *Neighboring structures*

In free shear layers, wakes, and jets the CS are formed in thin layers so that the main effect of the surrounding flow on the CS must be caused by adjacent or nearly adjacent CS. This is quite different to boundary layers where each CS is surrounded by other CS (Fig. 3b).

One could characterize these interactions as $1 + 1 + 1 + \dots$. These kinds of interactions can be idealized by considering the interactions between pairs of vortices. Such studies have yielded useful conservation conditions (Aref 1983), and insights into whether the vortices go round each other or merge or pair (e.g., Kiya et al. 1986).

(iii) *Many structures or a mean field?*

In turbulent boundary layers each CS is surrounded by others, and also by small-scale incoherent motion. In such cases it is no longer profitable to examine each interaction between the structures; it is more practical to represent the whole velocity field as that of the CS, U , plus a mean velocity field, \bar{u} , induced by the vorticity within all the CS, and a random component, u' to represent on the large scale the random locations of the CS, and on the small scale the incoherent motions (Fig. 3c). In other words, $1 + \infty + \infty'$, is equivalent to $U + u + u'$.

At present we understand little about the mechanics of the interaction between a finite volume of fluid containing vorticity and the surrounding flow. Most research on the dynamics of turbulence has been focused on the interaction between small perturbations and various kinds of mean flow, e.g., Townsend (1976) or Landahl & Mollo-Christiansen (1986). This is perhaps surprising since Prandtl's (1925) mixing length theory is based on a qualitative model of how "lumps of fluid" — Flüssigkeit ballen — interact with a shear flow.

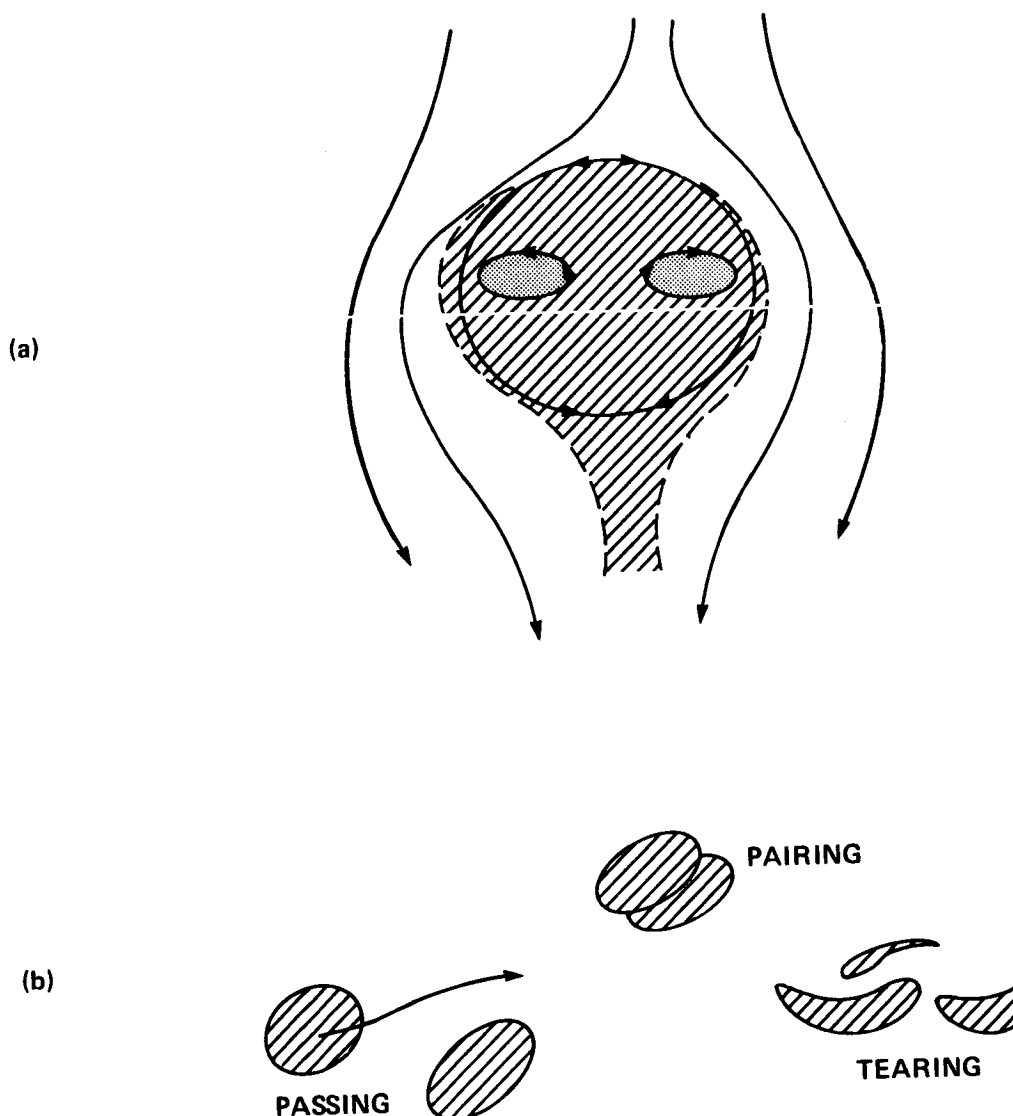


FIGURE 3. (a) A ring vortex in a uniform flow showing slow shedding of vorticity downstream. (b) Interaction between a Coherent Structure (CS) and neighboring CS (1+1 ...).

Some general questions about this problem were set out by Hunt (1987):

- i) What is the applied force and velocity of a volume V in a non-uniform unsteady flow with velocity u ? For inviscid flow (a good idealization for a short time), analytical expressions have recently been obtained for spherical or cylindrical volumes moving in shearing or uniformly straining flows. The initial movements of a lump—or CS—when displaced in a shear flow are largely controlled by inertial forces, in particular the added mass and lift forces. One finds that transverse displacements generate streamwise velocities of the lumps and thence Reynolds stresses—the CS analogy of the small perturbation Reynolds stress found in RDT or second-order calculations (Fig. 3d).
- (ii) How does the volume deform as it is accelerated when displaced across a shear flow? Flow visualization of the eddies or CS in a turbulent boundary layer show that as they are ejected from the wall form into “mushroom” shapes. These are very similar to the shapes of vortex sheets surrounding volumes of fluid which are suddenly introduced into jets (Coelho & Hunt 1987). In both cases the vortex sheets roll up into concentrated vortices characteristic of the mushroom

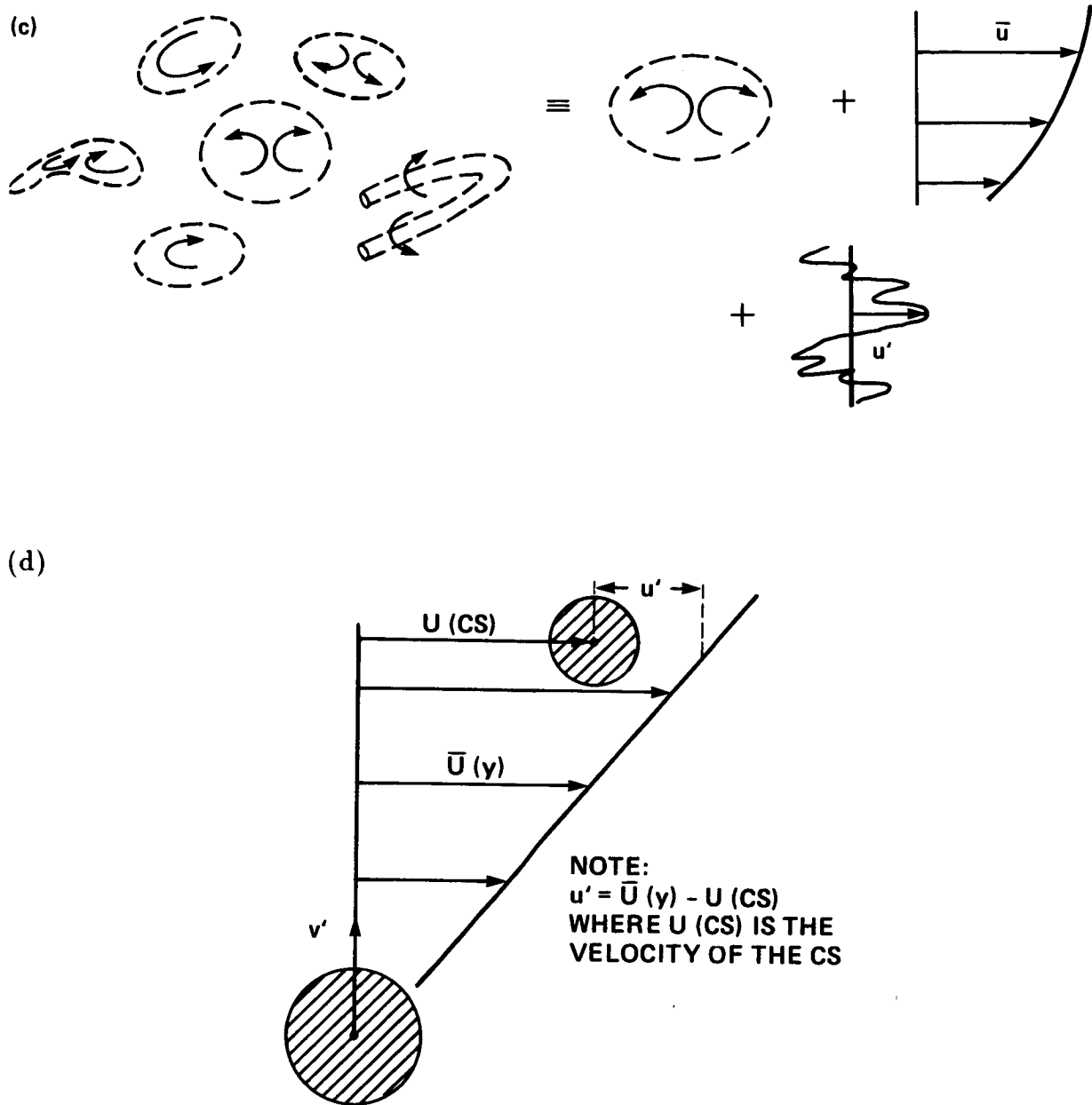


FIGURE 3. (c) Interaction between a CS and surrounding CS — equivalent to the interaction with a mean flow \bar{u} and turbulence u' . (d) Movement of a volume of fluid across a shear flow leading to the generation of Reynolds stress, $-u'v'$ — an idealization of the mechanics of a CS in a shear flow (Hunt 1987).

structures. These vortices appear to have forms that persist—which of course is one of the necessary features of CS.

The other approach to analyzing the dynamics of CS is to take a typical form of the vorticity distribution in a CS and to compute its development in an appropriate shear flow. That has certainly led to some interesting insights (Moin et al. 1986). But it will be necessary to conduct many such computations to obtain general concepts from them.

4. Effects of coherent structures on the whole flow

Since coherent structures are regions of vorticity they induce a velocity field both within them and outside them. Consequently, they affect the mean and the fluctuating components of the velocity field. Because they contain the largest and most energetic scales of motion the CS contribute a significant proportion of the total energy of the turbulence, and the Reynolds stress. The actual proportion depends on the precise definition of the CS (cf. Adrian 1987).

To compute the velocity fields affected by the CS it is necessary to account for all the key dynamical processes that affect the movement and the strength of the CS during its "life." Recent experiments, and detailed analysis of CS found in direct simulations of turbulent shear flows, are beginning to make this possible (Hussain et al. 1987).

Three examples of dynamical processes that need to be considered are: (i) amplification of the small-scale vorticity of the surrounding flow at the stagnation and straining regions around the CS, caused by the relative motion between the CS and the flow. This is similar to the amplification around bluff bodies and cross jets in turbulent flows (Hussain 1986; Hunt 1973) (Fig. 4); (ii) distortion of the vorticity and amplification of the "incoherent" turbulence within the CS, by the internal straining motions and the shear layers on the boundary of the CS. These are particularly important for determining the growth of the CS, i.e., controlling the spreading of the vorticity of the CS. They also largely control (iii) the detrainment of vorticity into the "wake" of the CS. This process has been studied in detail for the simplest type of CS, namely the vortex ring, and the somewhat more complex jet in a cross flow (Maxworthy, 1987; Coelho & Hunt 1987). For those CS it was found that at high enough Reynolds number the shed vorticity produces an unstable velocity distribution similar to that of a bluff body. This is another mechanism whereby one CS can produce another CS and small-scale turbulence in the surrounding flow. This essentially depends on a diffusion process initially, whereas in the free shear layer the secondary structures were produced by inviscid processes.

5. Concluding Remarks

These suggestions for topics of investigation into the dynamics of CS in fact follow many of the lines of study that are being followed at the University of Houston by Prof. Hussain and at the Center for Turbulence Research at Stanford/NASA Ames. There is perhaps one area of significant difference in that at this stage it is not so clear to me how the detailed mechanics of the CS will emerge from interpreting conditionally sampled velocity measurements in terms of conditional joint probability density distributions. This approach may lead to the prediction of certain useful statistics of the flow, but probably not to the dynamics of individual structures. However, the actual conditionally sampled measurements of velocity will help in elucidating the velocity/vorticity distributions in the CS, which is necessary for the dynamical studies outlined here.

I am grateful to Fazle Hussain for organizing the seminar on coherent structures at the CTR summer school, and for many interesting discussions on coherent structures, which this paper reflects. I am also grateful to the organizers of the summer school, in particular Parviz Moin and John Kim, who gave me some interesting other perspectives on coherent structures and how to analyze them.

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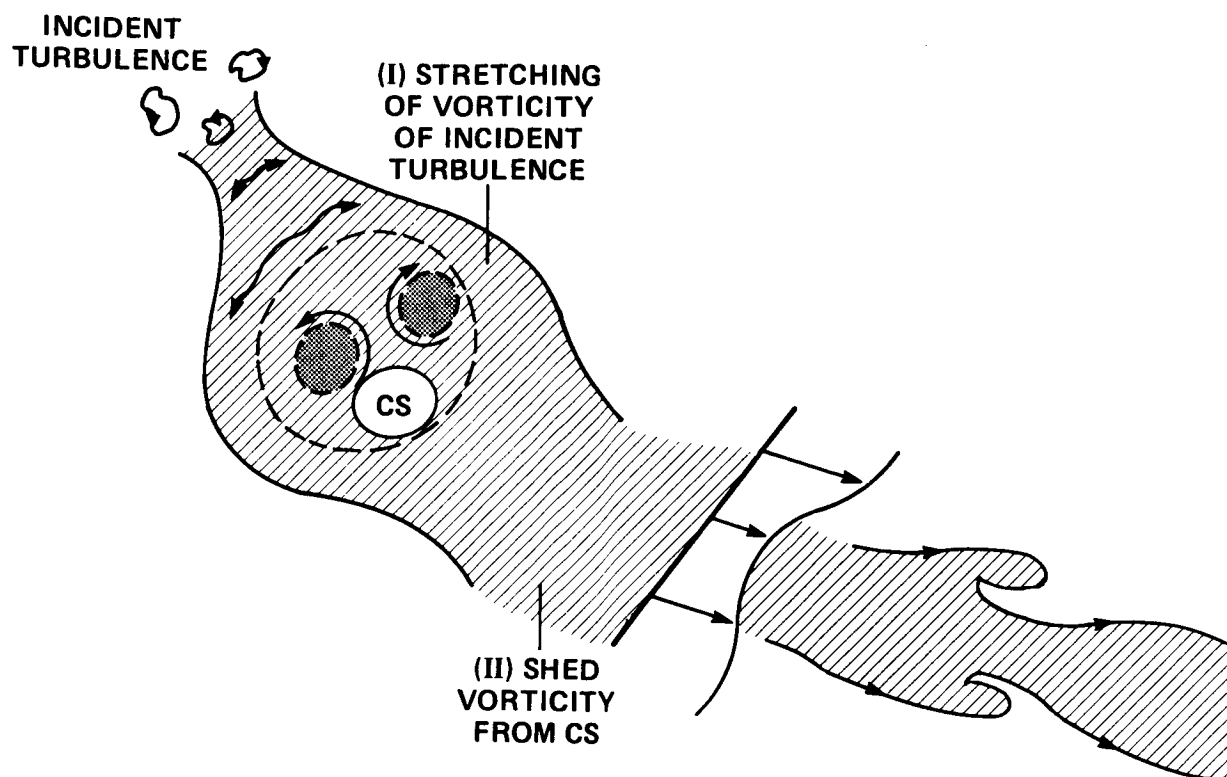


FIGURE 4. Effect of a CS on the surrounding flow in high Reynolds number turbulence. (I) Amplification of turbulence in the surrounding flow. (II) Shedding vorticity which leads to further turbulence in the surroundings.

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